2017 Technology Gap List
Assessment Review

Brendan Crill
Deputy Technology Development Manager
Exoplanet Exploration Program

21 October 2016

Success Criteria for this review

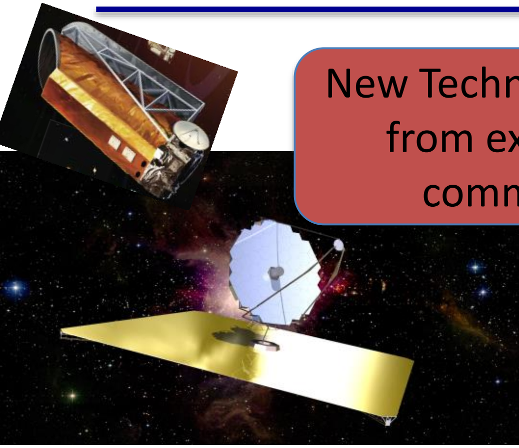
- **Has each technology gap submitted by the community been handled in an appropriate fashion, consistent with the selection and prioritization criteria?**

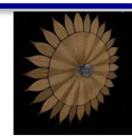
- **Are the scores in impact, urgency, and trend for each technology gap reasonable?**

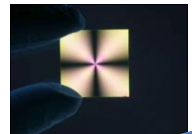
- **Is the final prioritized gap list a good reflection of the needs of the exoplanet community?**

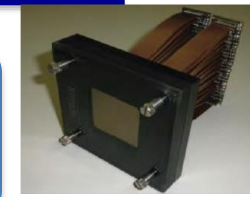
ExEP Technology Selection and Prioritization Process

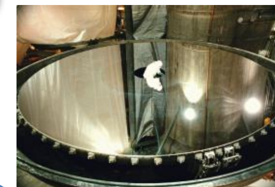
Exoplanet Exploration Program











New Technology Gaps from exoplanet community

Technology Gaps carried over from previous year

Selection: enables or enhances direct detection and characterization of exoplanets?

Neither enhancing nor enabling → not accepted

No, but could benefit exoplanet science → **List of Technologies that Benefit Exoplanet Science, aka "Watch List"**

Yes → Prioritize technologies according to criteria (Impact, Urgency, and Trend)

Selection and Prioritization Criteria:

- Peer reviewed
- Exo-TAC reviewed

ExEP Technology Gap List

Reviewed by Exo-TAC

Technology Selection and Prioritization Process

Exoplanet Exploration Program

ID	Activity	Date
1	Technology needs input window opens	06/08/16
	email all three PAGs: Technology Gap Lists, input forms, process explanation	
	presentation at June ExoPAG	06/12/16
2	Technology window closes	08/26/16
3	Technology Gap Selection and Prioritization Criteria Peer Review	09/08/16
	Selection and Prioritization Criteria Review by independent review board convened by ExoTAC	09/21/16
4	Technology Gap Assessment Peer Review	10/07/16
	Technology Gap Assessment Review by review board convened by ExoTAC	**10/21/16**
5	Technology Gap Lists inform TDEM amendment	mid-Nov
	Technology amendment released through NSPIRES	mid-Dec
6	ExEP Technology Plan Appendix updated and posted	12/22/16
	Presentation at January ExoPAG	01/02/17
7	TDEM Proposal Deadline	03/17/17
8	TDEM Awards Selected	Aug 2017

Selection Criteria

1. **Technology Gaps considered for tracking and development by the ExEP must support APD exoplanet science missions:**
    - as described in the Astrophysics Implementation Plan
    - directed through the Science Mission Directorate
    - selected through open competition
    - or described in the APD 30-year roadmap

2. **The subset of these gaps that either enables or enhances the direct detection and characterization of exoplanets, are prioritized onto the ExEP Technology Gap List.**
    - Technologies that address these gaps are the ones prioritized for development and considered for resource allocation
    - The list is published in the annual Technology Plan Appendix
    - Some of these technologies may be funded outside of the ExEP and will require collaboration amongst programs.

3. **The remaining technology gaps are considered to benefit exoplanet science and will be captured onto a second list: “List of Other Technology Opportunities That May Benefit Exoplanet Science” in the annual Technology Plan Appendix**
    - These gaps will be tracked and re-evaluated annually for potential prioritization

Gaps input from the community

- **Received 21**
  - 7 from LUVOIR STDT
  - 2 from HabEx STDT
  - 8 from Far-IR Surveyor STDT
  - 4 from community at large
- **Most can be consolidated with existing gaps or each other**
- **Four new additions to the enabling/enhancing gap list**
  - UV Ultra-low Noise Detector (LUVOIR)
  - UV/NIR/Vis Mirror Coatings (LUVOIR/HabEx)
  - Extreme Precision Ground-based Radial Velocity (HabEx)
  - Mid-IR Spectral Coronagraph (FIRS)
- **Combine with the 14 existing gaps (9 Coronagraph, 5 Starshade)**
- **3 gaps for "watch list":**
  - Sub-K coolers
  - Advanced cryocoolers
  - mid-IR ultra-low noise detector

Coronagraph gaps carried over from 2016 (1/2)

Contrast	CG-2	Coronagraph Optics and Architecture	Coronagraph optics and architecture that suppress diffracted starlight by a factor of ≤ 10^{-9} at visible and infrared wavelengths.	6×10^{-10} raw contrast at 10% bandwidth across angles of 3-16 λ/D demonstrated with a linear mask and an unobscured pupil in a static vac lab env't (Hybrid Lyot) < 8.8×10^{-9} raw contrast at 10% bandwidth across angles of 3-9 λ/D demonstrated with a circularly-symmetric mask and obscured pupil in a static vacuum lab env't (WFIRST)	Coronagraph masks and optics capable of creating circularly symmetric dark regions in the focal plane enabling raw contrasts ≤ 10^{-9}, with minimal contribution from polarization aberration, IWA ≤ 3 λ/D, throughput ≥ 10%, and bandwidth ≥ 10% on obscured/segmented pupils in a simulated dynamic vacuum lab environment.
Angular Resolution (plus sensitivity, integration time, and planet yield)	CG-1	Large Aperture Primary Mirrors	Large monolith and multi-segmented mirrors that meet tight surface figure error and thermal control requirements at visible wavelengths.	Monolith: 3.5m sintered SiC with < 3 um SFE (Herschel) 2.4m ULE with ~ 10 nm SFE (HST) Depth: Waterjet cutting is TRL 9 to 14", but TRL 3 to >18". Fused core is TRL 3; slumped fused core is TRL 1. Segmented: 6.5m Be with 25 nm SFE (JWST) Non-NASA: 6 dof, 1-m class SiC and ULE, < 20 nm SFE, and < 5 nm wavefront stability over 4 hr with thermal control	Aperture: 4m - 12m; SFE < 10 nm rms (wavelength coverage 400 nm - 2500 nm) Wavefront stability better than 10 pm rms per wavefront control time step. Segmented apertures leverage 6 DOF or higher control authority meter-class segments for wavefront control. Environmentally tested.
Detection Sensitivity	CG-8	Ultra-Low Noise, Large Format Visible Detectors	Low-noise visible detectors (200-1000 nm) for faint exoplanet characterization with an Integral Field Spectrograph	1kx1k silicon EMCCD detectors provide dark current of 7×10^{-4} e-/px/sec; CIC of 2.3x10-3 e-/px/fram; effective read noise < 0.2 e- rms (in EM mode) after irradiation when cooled to 165.15K (WFIRST). 4kx4k EMCCD fabricated but still under development.	Effective read noise < 0.1e- rms; CIC < 3×10^{-3} e-/px/fram; dark current < 10^{-4} e-/px/sec tolerant to a space radiation environment over mission lifetime. ≥ 2k x 2k format
Detection Sensitivity	CG-9	Ultra-Low Noise, Large Format Near Infrared Detectors	Near infrared wavelength (900 nm to 2.5 μm), extremely low noise detectors for exo-earth spectral characterization with Integral Field Spectrographs.	HgCdTe photodiode arrays have read noise <~ 2 e- rms with multiple non-destructive reads; dark current < 0.001 e-/s/pix; very radiation tolerant (JWST). HgCdTe APDs have dark current ~ 10-20 e-/s/pix, RN << 1 e- rms, and < 1kx1k format Cryogenic (superconducting) detectors have essentially no read noise nor dark current; radiation tolerance is unknown.	Read noise << 1 e- rms, dark current < 0.001 e-/pix/s, in a space radiation environment over mission lifetime. ≥ 2k x 2k format
Contrast Stability	CG-6	Segment Phasing Sensing and Control	Multi-segment large aperture mirrors require phasing and rigid-body sensing and control of the segments to achieve tight static and dynamic wavefront errors.	6 nm rms rigid body positioning error and 49 nm rms stability (JWST error budget) SIM and non-NASA: nm accuracy and stability using laser metrology	Systems-level considerations to be evaluated but expect will require less than 10 pm rms accuracy and stability.

Last year, we listed coronagraph and starshade gaps separately.
This year, we'll merge into one list.

Coronagraph gaps carried over from 2016 (2/2)

Contrast Stability	CG-7	Telescope Vibration Control	Isolation and damping of spacecraft and payload vibrational disturbances	80 dB attenuation at frequencies > 40 Hz (JWST passive isolation) Disturbance Free Payload demonstrated at TRL 5 with 70 dB attenuation at "high frequencies" with 6-DOF low-order active pointing.	Monolith: 120 dB end-to-end attenuation at frequencies > 20 Hz. Segmented: 140 dB end-to-end attenuation at frequencies > 40 Hz. End-to-end implies isolation between disturbance source and the telescope.
Contrast	CG-3	Deformable Mirrors	Environment-tested, flight-qualified large format deformable mirrors	Electrostrictive 64x64 DMs have been demonstrated to meet ≤ 10^{-9} contrasts and < 10^{-10} stability in a vacuum environment and 10% bandwidth; 48x48 DM passed random vibe testing.	4 m primary: ≥ 96x96 actuators 10 m primary: ≥ 128x128 actuators Enable raw contrasts of ≤ 10^{-9} at ~20% bandwidth and IWA ≤ 3 λ/D Flight-qualified device and drive electronics (radiation hardened,environmentally tested, life-cycled including connectors and cables) Large segment DM needs possible for segmented telescopes.
Contrast Stability	CG-5	Low-Order Wavefront Sensing and Control	Sensing and control of line of sight jitter and low-order wavefront drift	< 0.5 mas rms per axis LOS residual error demonstrated in lab with a fast-steering mirror attenuating a 14 mas LOS jitter and reaction wheel inputs; ~ 100 pm rms sensitivity of focus (WFIRST). Higher low-order modes sensed to 10-100 nm WFE rms on ground-based telescopes.	Sufficient fast line of sight jitter (< 0.5 mas rms residual) and slow thermally-induced (≤ 10 pm rms sensitivity) WFE sensing and control to maintain closed-loop < 10^{-9} raw contrast with an obscured/segmented pupil and simulated dynamic environment.
Contrast	CG-4	Post-Data Processing	Post-data processing techniques to uncover faint exoplanet signals from residual speckle noise at the focal-plane detector.	Few 100x speckle suppression has been achieved by HST and by ground-based AO telescopes in the NIR and in contrast regimes of 10^{-4} to 10^{-5}, dominated by phase errors.	A 10-fold contrast improvement in the visible from 10^{-9} raw contrast where amplitude errors are expected to be important (or a demonstration of the fundamental limits of post-processing)

Starshade gaps carried over from 2016

	ID	Title	Description	Current Capabilities	Needed Capabilities
Optical Performance and Model Validation	S-2	Optical Performance Demonstration and Validated Optical Model	Experimentally validate the equations that predict the contrasts achievable with a starshade.	3×10^{-10} contrast at 632 nm, 5 cm mask, and ~500 Fresnel #; validated optical model 9×10^{-10} contrast at white light, 58 cm mask, and 210 Fresnel #	Experimentally validate models predicting contrast to $\leq 10^{-10}$ just outside petal edges in scaled flight-like geometry with Fresnel numbers ≤ 20 across a broadband optical bandpass.
	S-1	Controlling Scattered Sun Light	Limit edge-scattered sunlight and diffracted starlight with optical petal edges that also handle stowed bending strain.	Machined graphite edges meet all specs but edge radius (10 um); etched metal edges meet all specs but in-plane shape tolerance (Exo-S design).	Integrated petal optical edges maintaining precision in-plane shape requirements after deployment trials and limiting contrast contribution of solar glint to $< 10^{-10}$ at petal edges.
Formation Sensing and Control	S-3	Lateral Formation Sensing	Demonstrate lateral formation flying sensing accuracy consistent with keeping telescope in starshade's dark shadow.	Centroid star positions to ≤ 1/100th pixel with ample flux. Simulations have shown that sensing and GN&C is tractable, though sensing demonstration of lateral control has not yet been performed.	Demonstrate sensing lateral errors ≤ 0.30 m accuracy at scaled flight separations (±1 mas bearing angle). Estimated centroid positions to ≤ 1/40th pixel with limited flux from out of band starlight. Control algorithms demonstrated with scaled lateral control errors corresponding to ≤ 1 m.
Deployment Accuracy and Shape Stability	S-5	Petal Positioning Accuracy and Opaque Structure	Demonstrate that a starshade can be autonomously deployed to within its budgeted tolerances after exposure to relevant environments.	Petal deployment tolerance (≤ 1 mm) verified with low fidelity 12m prototype and no optical shield; no environmental testing (Exo-S design).	Deployment tolerances demonstrated to ≤ 1 mm (in-plane envelope) with flight-like, minimum half-scale structure, simulated petals, opaque structure, and interfaces to launch restraint after exposure to relevant environments.
	S-4	Petal Shape and Stability	Demonstrate a high-fidelity, flight-like starshade petal meets petal shape tolerances after exposure to relevant environments.	Manufacturing tolerance (≤ 100 μm) verified with low fidelity 6m prototype and no environmental tests. Petal deployment tests conducted but on prototype petals to demonstrate rib actuation; no shape measurements.	Deployment tolerances demonstrated to ≤ 100 μm (in-plane envelope) with flight-like, minimum half-scale petal fabricated and maintains shape after multiple deployments from stowed configuration.

2017 Prioritization Criteria

Impact (weight: 10)	4: Critical technology - required to meet mission concept objectives; without this technology, applicable missions would not launch
	3: Highly desirable - not mission-critical, but provides major benefits in enhanced science capability, reduced critical resources need, and/or reduced mission risks; without it, missions may launch, but science or implementation would be compromised
	2: Desirable - not required for mission success, but offers significant science or implementation benefits; if technology is available, would almost certainly be implemented in missions
	1: Minor science impact or implementation improvements; if technology is available would be considered for implementation in missions

Urgency (weight: 10)	4: reduced risk needed for missions currently in pre-formulation or formulation.
	3: In time for the Decadal Survey (2019); not necessarily at some TRL but reduced risk by 2019.
	2: Earliest projected launch date < 15 yr (< 2030)
	1: Earliest projected launch date > 15 yr (> 2030)

Trend (weight: 5)	4: (a) no ongoing current efforts, or (b) little or no funding allocated
	3: (a) others are working towards it but little results or their performance goals are very far from the need, (b) funding unclear, or (c) time frame not clear
	2: (a) others are working towards it with encouraging results or their performance goals will fall short from the need, (b) funding may be unclear, or (c) time frame not clear
	1: (a) others are actively working towards it with encouraging results or their performance goals are close to need, (b) it's sufficiently funded, and (c) time frame clear and on time

Footnote: to be deemed "ready," the technology is available to NASA at TRL 6 by the earliest possible Preliminary Design Review (PDR) of a mission; or at TRL 5 by the start of Phase A

Feedback from Peer Review

- **The new language for Urgency:**
  - the technology gap's "needed capabilities" may exceed the needed capabilities for the mission that is in formulation or pre-formulation: for example, the "needed capabilities" for CG-2 (Coronagraph architecture) goes beyond what WFIRST needs. ***In scoring the gaps, address the needed capabilities***
  - The "pre-formulation" or "formulation" language for urgency 3 is a little difficult: are LUVOIR/Habex/FIRS in "pre-formulation"? ***In scoring the gaps, we assumed that urgency 4 is for WFIRST, urgency 3 is for a technology gap aimed at influence the decadal survey (i.e. for Habex or LUVOIR)***

2017 Scores and Prioritization

Exoplanet Exploration Program

Gap ID	Gap Title	Impact	Urgency	Trend	Total
CG-9	NIR Ultra-Low Noise Detector	4	3*	4*	90
S-2	Optical Performance Demonstration and Optical Modeling	4	4	2	90
CG-2	Coronagraph Architecture	4	3	3	85
CG-1	Large Aperture Mirrors	4	3	3	85
CG-6	Segment Phasing Sensing & Control	4	3	3	85
CG-7	Telescope Vibration Control	4	3	3	85
S-1	Control Edge-Scattered Sunlight	4	4	1	85
S-3	Lateral Formation Flying Sensing	4	4	1	85
S-4	Petal Shape	4	4	1	85
S-5	Inner Disk Deployment	4	4	1	85
S-6	Petal Unfurling	4	4	1	85
CG-3	Low-Order Wavefront Sensing and Control	4	3	2	80
CG-5	Deformable Mirrors	4	3	2	80
CG-8	Visible Ultra-Low Noise Detector	4	3	2	80
M-1	Extreme Precision Radial Velocity	3	3	3	75
CG-4	Post-Data Processing	4	2	2	70
CG-9	UV/NIR/Vis mirror coatings	3	3	2	70
CG-10	Mid-IR Spectral Coronagraph	2	3	3	65
CG-11	UV Ultra-low noise detector	2	3	2	60

Notes:

- Enabling -> impact=4
- Enhancing -> impact=2,3
- Urgency:
  - STDT gaps all get a 3
  - Starshade gaps get 4
  - Data processing is instrument-specific: urgency 2
- SS project: starshade gaps get 1-2 in Trend
- * n.b.: NIR detectors may change: noise requirements may only be at <1.7 μm (waiting on LUVOIR/HabEx coronagraph long-wave cutoff)
- Little spread in scores among “enabling” gaps: nearly all 80,85,90

Did we meet the success criteria for this review?

- Has each technology gap submitted by the community been handled in an appropriate fashion, consistent with the selection and prioritization criteria?
- Are the scores in impact, urgency, and trend for each technology gap reasonable?
- Is the final prioritized gap list a good reflection of the needs of the exoplanet community?